Results from the AST/RO Survey of the Galactic Center Region

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We have used the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), a 1.7m diameter single-dish submillimeter-wave telescope at the geographic South Pole, to determine the physical state of gas in the Galactic Center region and assess its stability. We present an analysis based on data obtained as part of an ongoing AST/RO key project: the large-scale mapping of the dominant cooling lines of the molecular interstellar medium in the Milky Way [1, 2, 3, 4]. These data are released for general use.

1 Introduction

The distribution of molecular gas in the Galaxy is known from extensive and on-going surveys in CO and ^{13}CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$; these are spectral lines which indicate the presence of molecular gas. These lines alone do not, however, determine the excitation temperature, density, or cooling rate of that gas. Observations of C I and the mid-J lines of CO and ^{13}CO provide the missing information, showing a more complete picture of the thermodynamic state of the molecular gas, highlighting the active regions, and looking into the dense cores. AST/RO can measure the dominant cooling lines of molecular material in the interstellar medium: the $^3P_1 \rightarrow {}^3P_0$ (492 GHz) and $^3P_2 \rightarrow {}^3P_1$ (809 GHz) fine-structure lines of atomic carbon (C I) and the $J = 4 \rightarrow 3$ (461 GHz) and $J = 7 \rightarrow 6$ (807 GHz) rotational lines of carbon monoxide (CO). These measurements can then be modeled using the large velocity gradient (LVG) approximation, and the gas temperature and density thereby determined. Since the low-J states of CO are in local thermodynamic equilibrium (LTE) in almost all molecular gas, measurements of mid-J states are critical to achieving a model solution of the radiative transfer by breaking the degeneracy between beam filling factor and excitation temperature.

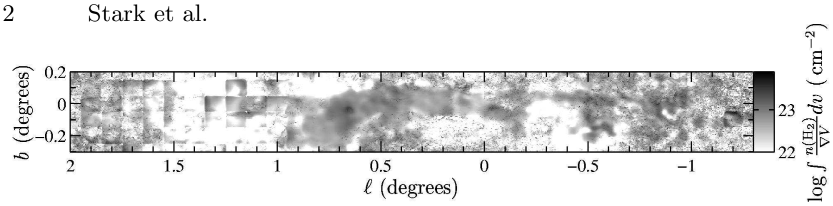

Fig. 1. Greyscale representation of molecular column density in the Galactic Center Region, from an LVG model using AST/RO survey data [1].

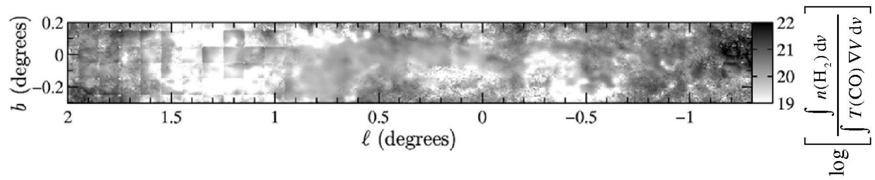

Fig. 2. Greyscale representation of the ratio of molecular column density (as derived from an LVG model, cf. Fig. 1) to the integrated brightness of the CO $J = 1 \rightarrow 0$ line [7]. If both these quantities were accurate measures of molecular column density, then the ratio would be a constant; the ratio actually varies by an order of magnitude either way around the mean.

2 AST/RO Survey Parameters

AST/RO has been operational in the submillimeter-wave atmospheric windows since 1995 [5, 6]. Essential to AST/RO's capabilities is its location at Amundsen-Scott South Pole Station, an exceptionally cold, dry site which has unique logistical opportunities and challenges. Among the key AST/RO projects is mapping of the Galactic Center Region. Sky coverage as of 2002 is $-1^{\circ}\!.3 < \ell < 2^{\circ}$, $-0^{\circ}\!.3 < b < 0^{\circ}\!.2$ with $0'\!.5$ spacing, resulting in spectra of three transitions at 24,000 positions on the sky [2, 1]. The data are available on the AST/RO website[4] for general use.

The C I emission has a spatial extent similar to the low-J CO emission, but is more diffuse [3, 4]. The CO $J = 4 \rightarrow 3$ emission is also found to be essentially coextensive with lower-J transitions of CO, indicating that even the $J = 4$ state is in LTE at most places; in contrast, the CO $J = 7 \rightarrow 6$ emission is spatially confined to far smaller regions [2]. Applying an LVG model to these data [1] together with data from the Bell Labs 7m [7, 8] yields maps of gas density and temperature as a function of position and velocity for the entire region. Kinetic temperature is found to decrease from relatively high values (> 70 K) at cloud edges to lower values (< 50 K) in the interiors. Typical pressures in the Galactic Center gas are $n(\mathrm{H}_2) \cdot T_{kinetic} \sim 10^{5.2}\,\mathrm{K\,cm^{-3}}$.

An estimate of the molecular column density can be obtained by integrating the LVG-derived density over all velocities [1], as shown in Figure 1.

[4] `http://cfa-www.harvard.edu/ASTRO`

An alternative estimate can be made utilizing the common assumption that the column density is proportional to the brightness of the $J = 1 \rightarrow 0$ CO line [9, 10]. Both of these estimates can be carried out on each line of sight, and their ratio plotted as a function of position, as shown in Figure 2. If the methodologies were mutually consistent, then the ratio should not vary with position. In fact the ratio varies *by two orders of magnitude*. Both methods incorporate rather ill-determined multiplicative constants, which can arbitrarily be adjusted to bring the two methods into agreement over some of the map but not all of it. The discrepancies are caused by variations in the excitation and optical depth of the CO lines, suggesting that the LVG method should be the more accurate method when submillimeter data are available.

3 Galactic Center Gas Stability

The dynamics of the Galactic Center region depend critically on whether the interstellar medium is self-gravitating or not [11]; given our estimate for the density of the molecular gas, we can now determine its stability against coagulation into self-gravitating lumps. Binney et al. [12] have suggested that gas in the Galactic Center will be found mostly on closed orbits, because gas thrown into a stellar system will tend to shock and violently damp until it settles onto closed, parallel streamlines. In the central bar of the Milky Way, the closed orbits fall into two families: the elongated x_1 orbits running parallel to the outer parts of the bar about 1 or 2 kpc from the center, and the roughly circular x_2 orbits located near the inner Lindblad resonance (ILR) of the bar at $\sim 350\,\mathrm{pc}$ and further inwards [13]. Gas falling into the system from outside first settles onto the x_1 orbits. As it continues to lose energy, it slides downwards through x_1 orbits of decreasing size until it gets to the inner x_1 orbits, which are self-intersecting, where it transitions onto the outer x_2 orbits [13, 11] near the ILR—there it will tend to accumulate, because inwards of the ILR the net torque on the gas by the bar reverses sign, so that gas inside the ILR is pushed outward while gas outside the ILR is pushed inward [14]. Gas therefore accumulates on the outer x_2 orbits near the ILR, growing more and more dense until it becomes self-gravitating at a density [14] of

$$n(\mathrm{H}_2) > \frac{0.3\kappa^2}{m_p G} \approx 10^{3.4}\,\mathrm{cm}^{-3}\,,$$

where $\kappa \approx 900\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ is the epicyclic frequency [13]. Gas on x_2 orbits appears in the data on a strip about $50\,\mathrm{km\,s^{-1}}$ wide extending from $(\ell,\, v) = (-1^\circ,\, -80\,\mathrm{km\,s^{-1}})$ to $(+1^\circ,\, +80\,\mathrm{km\,s^{-1}})$. Our LVG model shows that the gas in this strip is near the critical density, indicating that it is only marginally stable against gravitational coagulation into one or two giant clouds [14]. This suggests a relaxation oscillator mechanism for starbursts in the Milky Way, where inflowing gas accumulates in a ring at 350 pc radius until the

critical density is reached, and the resulting instability leads to the sudden deposition of a Giant Molecular Cloud onto the Galactic Center.

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